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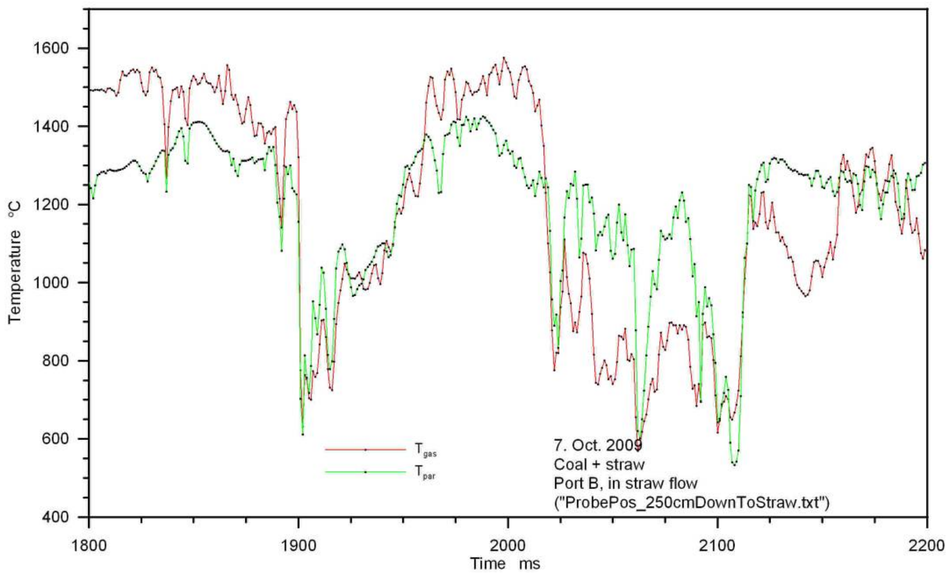

Sønnik Clausen, Alexander Fateev, Karsten Lindorff Nielsen, Vadim Evseev

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By
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Abstract

Project is focused on fast time-resolved infrared measurements of gas temperature and fast IR-imagining of flames in various combustion environments. The infrared spectrometer system was developed in the project for fast infrared spectral measurements on industrial scale using IR-fibre-optics. Fast time- and spectral-resolved measurements in 1.5-5.1 μm spectral range give information about flame characteristics like gas and particle temperatures, eddies and turbulent gas mixing. Time-resolved gas composition in that spectral range (H_2O, CH_4, CO_2, CO) which is one of the key parameters in combustion enhancement can be also obtained. The infrared camera was also used together with special endoscope optics for fast thermal imaging of a coal-straw flame in an industrial boiler. Obtained time-resolved infrared images provided useful information for the diagnostics of the flame and fuel distribustion. The applicability of the system for gas leak detection is also demonstrated. The infrared spectrometer system with minor developments was applied for fast time-resolved exhaust gas temperature measurements performed simultaneously at the three optical ports of the exhaust duct of a marine Diesel engine and visualisation of gas flow behaviour in cylinder.

Projektets fokus er hurtige infrarøde målinger af gastemperatur og hurtig infrarød visualisering af brændselsfordeling i flammer.. Et infrarødt spektrometer system, bestående af et IR-kamera (FPA) og IR gitter spektrometer, blev bygget i projektet til hurtige infrarøde spektroskopiske målinger i såvel laboratorie som industriel skala. Hurtige målinger i spektralområde fra 1.5 til 5.5 μm indeholder information om flammers gas- og partikeltemperatur, hvirvler og turbulent gasopblanding kan følges tidsopløst. System kan desuden anvendes til tidsopløst måling af gaskoncentrationer (H_2O, CH_4, CO_2, CO) og visualisering af gas flow. Det udviklede og testede system er anvendt til hurtige tidsopløst målinger af gastemperatur i kul-halm flamme på Studstrupsværkets blok 4. Et specielt IR endoskopoptik til måling på flamme i et industrielt fyrrum. Opnåede tidsopløste infrarøde billeder gav nyttig information om partikelfordeling og opblanding. Systemets anvendelighed til visualisering af gaslæk og gasflow er også demonstreret. Det infrarøde spektrometer system er med mindre udbygninger blevet anvendt til hurtige tidsopløste målinger af udstødningsgastemperatur samtidigt ud for tre optiske åbninger i udstødningsrør kort efter ventil på en Diesel skibsmotor. Desuden er gasflow for første gang visualiseret i cylinder under drift i diesel motor.

Preface

The mixing of cold and hot gas flows is like mixing water and oil, i.e. it is difficult to obtain perfect mixing and it requires optimized injection of flows. Furthermore, biomass dust is a high volatile fuel with broad particle size distribution and outcome from several measurements campaigns on biomass fired units indicate that gas mixing is poorer than imagined.

Project is focused on fast time-resolved IR-measurements of gas temperature and fast IR-imagining of flames in various combustion environments. Fast time- and spectral-resolved measurements in 1.5-5.1 μm spectral range give information about flame characteristics like gas and particle temperatures, eddies and turbulent gas and particle mixing. Time-resolved gas concentration measurements in that spectral range (H_2O, CH_4, CO_2, CO) which is one of the key parameters in combustion enhancement can be also obtained.

The purpose of the project is an investigation of fast transient phenomena in various flames and its boundary regions on the full scale through mapping of the gas temperature and IR flame spectral-resolved imaging.

Kgs. Lyngby (Denmark), February 2012

Sønnik Clausen
Senior Scientist

Contents

1. Introduction

1.1. Background

Risø has applied FTIR spectroscopy with fibre optical probes for years in many large-scale flames and boilers. The data rate was mostly limited to a few Hz as the FTIR spectrometer is based on a mechanical movement of a mirror, i.e. we have been able to follow temporal macro time fluctuations of gas temperature and composition. In this project we would like to go from a data rate of a few Hz towards kHz region in order to follow micro scale temperature fluctuations. Laser based methods are even faster, but the developed infrared spectrometer system is this project is far more flexible to use, lower system cost and easier to apply on large scale faciliteties.

Fast transient phenomena play an important role in various areas of technique and science, e.g. mixing of chemically reacting flows, temperature bifurcations and instabilities in flame development and propagation. In the last decade with a great development in fast imaging detectors from UV to IR spectral ranges it became possible to get a deep insight into various chemical and physical processes with down to a few nanoseconds of the time resolution which leaded to significantly better understanding of the processes nature with followed technical improvement in corresponding techniques.

It is recognized that the conversion of biomass particles differs from the conversion of pulverized coal in suspension-fired boilers. There are evidences that co-firing significantly impacts into near burner flow, species and temperature distributions that lead to uncompleted mixing problem and burn-out problems. However it seems that the time resolution of around 0.01-1 seconds in, for example, an IR flame imaging would be even not enough in order to understand mixing phenomena and flame propagation. Thus the time resolution needed for “a capture” of fast transient features might be a few microseconds. Modern fast IR cameras can record images with such a short measurement time. A exposure time of approx. 1 ms appears to be sufficient in most cases for large scale pulverised flames.

Project is focused into fast time-resolved IR-measurements of gas temperature and fast IR-imagining of flames in various combustion environments. Fast time- and spectral-resolved measurements in 1.5-5.1 micrometer spectral range give information about flame micro and macro characteristics like gas and particle temperatures, eddies and turbulent gas mixing. In the project, a fast IR camera (CEDIP Infrared Systems, Titanium, detector: 560M, InSb, 640×512 pixels) having exposure time down to 7 microseconds and being sensitive in the 1.5-5.1 micrometer range was used together with a grating spectrometer (Princeton Instruments, Acton SP2150, 0.150 m Imaging Dual Grating Monochromator/Spectrograph). Time-resolved gas concentration measurements in that spectral range (H_2O, CH_4, CO_2, CO) which is one of the key parameters in combustion enhancement can be also obtained.

1.2. Project purpose

The main purpose of the project is an investigation of fast transient phenomena in various flames and its boundary regions on the full scale through mapping of the gas temperature and IR spectral-resolved flame imaging.

1.3. Objectives

The main objectives were to:

1. Combine existing new fast IR camera with an endoscope probe, IR probe head and an imaging spectrometer/monochromator for fast field and spectral-resolved imaging of flames and its boundaries.

2. Test the developed system in the lab and on full-scale combustion environments.
All full-scale measurements performed in project were coordinated with other on-going projects.

3. Perform full-scale time-resolved measurements on DONG's power plants operated on multi-fuel loads at typical operation conditions in the combustion zone, flame boundary, and at the burner walls which helps in the modelling and design optimization of combustion systems and processes involving use of biomass, waste and other renewable fuels.

The project is divided into three main work packages reflecting the objectives.

1.4. Relevance

The project supports Danish strategy to extend the use of biomass resources but not only. Fast IR-imaging will further improve our knowledge about various full scale combustion systems which is very important for their maintenance, optimization and future design. Improved or newly designed systems will further reduce environmental impact of thermal power generation and improve utilization of fossil and renewable fuels.

The project results will stimulate further development of sensors for monitoring and control of processes in order to track dynamic behaviour of flow, mixing, flame ignition, development and propagation. Developed in the project technique will be a powerful tool in experimental input to the CFD calculations.

DTU Chemical Engineering (before 1. January 2012 Risø DTU, Optical Diagnostics Group) is involved in many R&D projects on energy in Denmark and abroad using non-contact measurement techniques. DTU Chemical Engineering possesses the Danish national reference laboratory for non-contact temperature measurements. The facilities and know-how at DTU Chemical Engineering are used in research projects and offered to customers around the world. This ensures impact and support of R&D energy activities in Denmark and modern globalization world.

CFD has become a powerful tool for calculation of gas flows in burners and boilers, but still information on real processes' behaviour is needed to understand results and limitations, and to improve the models.

1.5. R&D Strategy

The project correlates with other PSO F&U projects as PSO 4792 Fællesprojekt, PSO 4805 "Kanaldannelse i fyrrum" and PSO 7333 "Combustion zone investigation and modelling in fuel flexible suspension fired boilers". The project also correlates with the EU HERCULES-Beta Project "Transient emission measurements in the exhaust duct" and "Thermal imaging in large diesel engines" carried out under Seventh Framework Program, Sustainable Surface Transport, grant agreement SCP7-GA-217878. The application is a logical extension of previous activities at DTU Chemical Engineering in gas temperature and visualization measurements to the short time scale in order to meet the demands on measurement techniques and modelling.

1.6. Business Strategy

Increasing electricity production from renewable resources, increasing integration of energy production systems, demands on pollutant reduction – all require the development of robust solutions. Therefore intelligent design of new, maintains and careful modification of existing power plants using available compounds will require in-depth understanding of process fundamentals.

Dong Energy Generation which owns a fleet of power plants has strong interest for the on-front fast measurement technique which was developed in the project. Measurements were performed on Dong's power plants.

1.7. Dissemination

Project results were disseminated through a publication in proceedings of a conference [11]. The project contributes to advances in combustion measurement technology and in detailed full scale data collection. This report on the project is publicly accessible where the project results are presented.

In the project, developed technique significantly improved our knowledge about fast temperature, particle fluctuations and gas mixing in various combustion processes and improved process modelling.

2. Infrared Spectrometer System for Fast Spectral Measurements

2.1. The Description of the System

An Infrared Spectrometer System [10, 11] for fast spectral measurements in the infrared (IR) spectral range was developed in the project.

The IR spectral range was chosen because many combustion species (H_2O, CH_4, CO_2, CO) have strong emission/absorption bands in the IR spectral range [1] which makes this range useful for combustion diagnostics. Therefore the system was optimized to work in the IR spectral range.

The system consists of a grating spectrometer (Princeton Instruments, Acton SP2150, 0.150 m Imaging Dual Grating Monochromator/Spectrograph) and an IR camera (CEDIP Infrared Systems, Titanium, detector: 560M, InSb, 640×512 pixels), Fig. 1. The IR camera is "looking" into the rear focal plane of the grating spectrometer where infrared spectra are formed by the grating. The spectra are then obtained from the infrared images by reading the intensities along the bright strips in the infrared images (see Fig. 1).

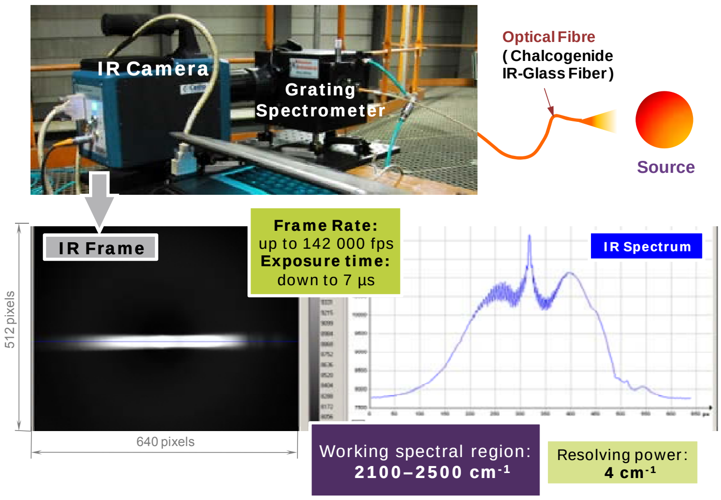


Figure 1. Infrared Spectrometer System for Fast Spectral Measurements. Upper picture: system used for flame temperature measurements at Studstrup Power Plant. Lower pictures:raw IR-image from grating spectrometer (left) and spectrum with absorption features from CO lines (right).

The InSb array of the IR camera enables detection in the 1700-10000 cm^{-1} range. The optical set-up of the system also has a long wave pass filter with cut-off at 3030 cm^{-1} (Spectrogon LP-3300 nm) which cuts the wave lengths in higher orders reflected by the grating at the same angles as the wave lengths in the working order. The IR camera was used with its native objective lens which gives the sharpest possible IR image of the rear focal plane of the spectrometer and in this way maximum possible spectral resolution is provided. Achieved spectral resolution (resolving power) was approx. 4 cm^{-1}. The coatings of the lenses in the objective lens provide overall transmittance in the region 2000-2857 cm^{-1}. The system is finally optimized to work in the range 2100-2500 cm^{-1} which is sufficient to cover the CO_2 absorption band at 4.3 µm. The left hot wing (on the lower wave number side) of this band was used for the calculation of gas temperature using the spectral emission-absorption method of temperature measurement [2] (see also Section 2.3 for details).

The radiation from the source under investigation is brought to the slit of the spectrometer by an optical fibre (chalcogenide IR-glass fibre). The use of fibre-optics gives a lot of flexibility and makes it possible to reach regions several meters (i.e. 5 or 8 m) inside industrial boilers. Specially designed water-cooled probes are used to insert and to protect the fibre when taking measurements inside industrial boilers [3, 4, 5, 6, 10] (see also Section 2.4).

The temporal resolution of the system is defined by the exposure time of the camera. The camera can be run with the exposure time of down to 7 microseconds and a frame rate of several kHz with windowing of the detector array. The full frame rate is limited to 100 Hz for the Ir-camera used..

2.2. Mathematical Model of Spectral Measurement

A static model of the spectral measurement is given by

$$S(\nu) = R(\nu)L(\nu) + B(\nu)$$

where ν is a wave number [cm^{-1}], $S(\nu)$ is received signal from a source (e.g. hot gas) [Digital Levels - uncalibrated “raw” units of the IR camera]; $L(\nu)$ is spectral radiance of the source [$W / m^2 \ sr \ m^{-1}$]; $R(\nu)$ is a response (or instrument) function [Digital Levels / ($W / m^2 \ sr \ m^{-1}$)]; $B(\nu)$ is constant background radiation [Digital Levels].

The response function $R(\nu)$ is obtained experimentally from known spectral radiances $L_{BB}(\nu,T_1)$ and $L_{BB}(\nu,T_2)$ of a blackbody radiation source at two different temperatures T_1 and T_2

$$R(\nu) = \frac{S_1(\nu) - S_2(\nu)}{L_{BB}(\nu,T_1) - L_{BB}(\nu,T_2)} \tag{1}$$

where $S_1(\nu)$ and $S_2(\nu)$ are measured signals [Digital Levels] from the blackbody radiation source at two respective temperatures; $L_{BB}(\nu,T)$ as a function of ν and T is given by Planck Radiation Law

$$L_{BB}(\nu,T) = \frac{2hc^2\nu^3}{e^{hc\nu/k_BT} - 1} \tag{2}$$

where the meaning of the constants can be found elsewhere, e.g. in [7].

Equation (1) is the model of calibration procedure which means that in order to calibrate the system (the Digital Levels) measurements of two signals $S_1(\nu)$ and $S_2(\nu)$ from a blackbody radiation source at two different temperatures as well as a measurement of the background radiation $B(\nu)$ are needed.

A simplified calibration can also be done if instead one of signals from the blackbody the background radiation is used corresponding to the spectral radiance of the blackbody at an ambient temperature T_{amb} . Provided that the ambient temperature is around room temperatures (300 K) and the temperature T_1 of the blackbody radiation source is about 1000 K, the term

$L_{BB}(\nu, T_{amb} \approx 300\,\mathrm{K})$ is much less than $L_{BB}(\nu, T_1 \approx 1000\,\mathrm{K})$ (see eq. (2)] and to a very good approximation can be accepted to be zero

$$R(\nu) = \frac{S_1(\nu) - B(\nu)}{L_{BB}(\nu, T_1)}, \tag{3}$$

i.e. only two measurements ($S_1(\nu)$ and $B(\nu)$] where the blackbody is at only one temperature are needed for the calibration.

The advantage is that the blackbody radiation source has a relatively long response time to stabilize at a given temperature. So the use of two temperatures of the blackbody is much less efficient. On the other hand it is possible to use two blackbodies however the exchange may lead to some changes within the optical path which introduces some uncertainty into the calibration results. The use of two temperatures, on the other hand, gives two strong signals for the calibration and the signal-to-noise ratio is higher in case when the calibration is made according to eq. (1) compared to the simplified scheme (3).

In this project, the calibration was made according to eq. (1) using two blackbodies for the laboratory test (see Section 2.3). The uncertainty brought by the exchange of the blackbodies was observed to be negligible. For the measurements on the industrial boiler (Section 2.4), the calibration was made according to eq. (3).

2.3. The Laboratory Test of the System

The system was tested for the gas temperature measurement using a lab scale burner producing stable flame with known axi-symmetric temperature profile [8]. The system was arranged as described in Section 2.1 except that CaF_2 lenses were used to focus the light from the flame and blackbody (see also the description of the measurements further) onto the entrance slit of the spectrometer instead of the optical fibre (see Fig. 2). A special care was taken to align the the lenses and to provide a narrow field of view together with a maximum possible signal level. CaF_2 lenses have transmittance in a wide spectral range as opposed to the optical fibre which has strong absorption in a short region within the CO_2 absorption band at 4.3 μm. The absorption from the fibre just slightly affects the hot left wing of the band which is used for the temperature measurement. The measurements in the industrial boiler (see Section 2.4) still have a good signal-to-noise ratio. But for the lab test maximum possible signal-to-noise ratio was provided with these CaF_2 lenses.

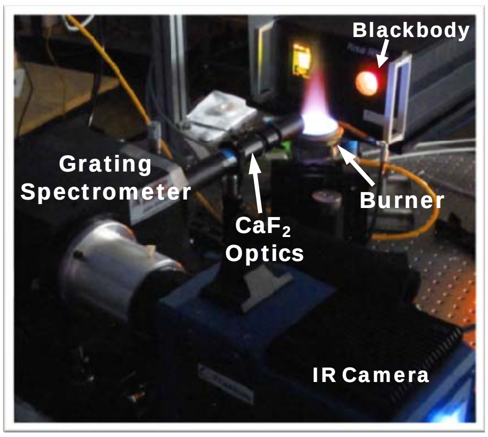


Figure 2. Test of the system in the laboratory at Risø, experimental layout for the flame temperature measurement.

The temperature was measured using the spectral emission-absorption method [2]. Together with the measurements for the calibration (eq. (1)], this method also requires to make the transmission and emission measurements of the flame. The transmission measurement is made with a reference source behind the flame. The reference source can be a blackbody radiation source or any other source with known spectral radiance.

The received spectral radiance $L_R(\nu)$ in the transmission measurements consists of $L_T(\nu)$, the transmitted by the flame reference source radiation ($L_0(\nu)$), and $L_E(\nu)$, the radiation emitted by the flame (Fig. 3). The latter is obtained in the emission measurements. The emission measurements are made simply when the reference source is blocked or removed from the field of view of the optical set-up.

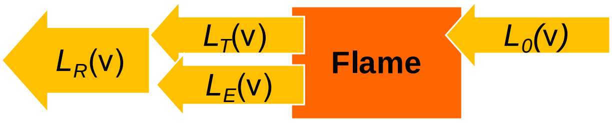


Figure 3. Schematic diagram of the measurements in the spectral emission-absorption method of gas temperature measurement (see the text for the meaning of the notation).

The spectral transmittance is given by

$$\tau(\nu) = \frac{L_T(\nu)}{L_0(\nu)} = \frac{L_R(\nu) - L_E(\nu)}{L_0(\nu)}$$

where $L_R(\nu)$, $L_E(\nu)$ and $L_0(\nu)$ are all measured spectral radiance in the transmission, emission and reference measurements. The reference measurement can be taken from the calibration measurements, e.g. $L_0(\nu) = L_{BB}(\nu, T_1)$.

The spectral absorptance is given by

$$\alpha(\nu) = 1 - \tau(\nu)\,. \tag{4}$$

Further, applying Kirchhoff's law, the average along the field of view gas temperature T_{GasAvg} can be obtained using the Planck radiation law (2) from the value which is calculated as

$$L_{BB}(\nu, T_{GasAvg}) = \frac{L_E(\nu)}{\alpha(\nu)}\,. \tag{5}$$

T_{GasAvg} is calculated from eq. (2) using the above value.

Described method gives the average along the field of view gas temperature in the flame [2], [9]. The average temperature of the laboratory burner was measured as described above by the infrared spectrometer system and measured average flame temperature was compared to the reference average flame temperature taken from [8] (see Fig. 4). In this way, the system was validated. The measurements were performed at 12 mm above the burner plate and the line-of-sight of the measurements was "looking" through the centre of the burner plate. The burner was operated at the stoichiometric combustion (equivalence ratio 1). The deviation from the reference temperature was found to be within 4 %. Deviation is mainly due to boundary effects as it is assumed that gas temperature is constant along the optical path in the flame (simple line of sight measurement).

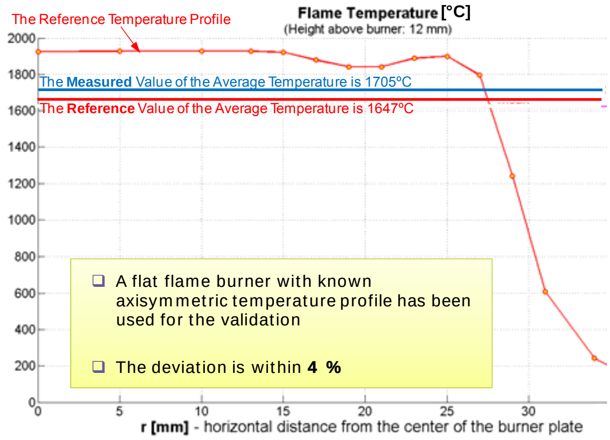


Figure 4. Average flame temperature (see the text for details): measured by the infrared spectrometer system (blue) and the reference value (red). The reference temperature profile is shown by the red line with yellow markers.

2.4. Fast Spectral Measurements in the Industrial Boiler

The infrared spectrometer system was successfully applied for spectral measurements on an industrial boiler at the Studstrup power plant, a biomass-coal power plant, unit 4 [10]. Some of boiler's burners were retrofitted to allow for simultaneous feeding of two separate pulverized fuels, coal and biomass (straw) [10]. The interest was to measure the temperature in different regions near such burner, e.g. above the burner, close to the straw region, etc., for the purpose of further analysis of the coal-biomass combustion.

A special 7 m long water cooled probe [10] (Fig. 5) was used to insert and to protect the IR fibre (chalcogenide IR-glass fibre) which was used to bring the radiation from inside the boiler to the entrance slit of the spectrometer.

The probe was designed with two water inlets to control the temperature inside the probe with fibre-optics (typically 21-33 ºC). Probe diameter is 60.3 mm and weight is approx. 55 kg. 1" hoses were used for inlet and outlet cooling water. Two fire hoses were used for water supply with a pressure of approx. 3.5 bar and 6 bar [10].

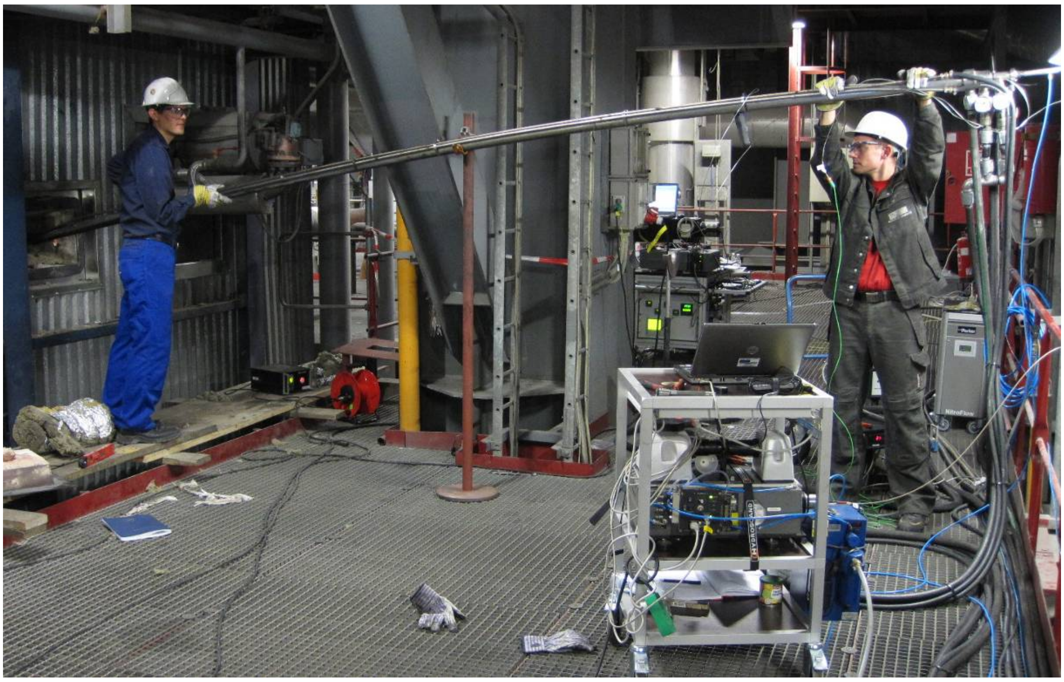


Figure 5. 7 m long water-cooled probe with the IR fibre inside inserted into the boiler [10].

A transportable blackbody was used to calibrate the infrared spectrometer system before and after the measurements. The calibration was made according to eq. (3). The temperature of the blackbody was T_1 = 897ºC ±3 ºC at 900 ºC set point according to certificate IR20075. This procedure is a part of the quality system to define uncertainty on temperature measurements. The calibration result before and after the measurements are compared to detect any changes in the system, e.g. attenuation of signal due to slag on ceramic probe tip, rotation of fibre during experiment or any other problems. Deviation in signal is usually below 1-2% [10].

It is possible to calculate the temperature of CO_2 and solid surfaces from the spectra using corresponding parts of the working spectral region. Gas temperature was found from emission at CO_2 band at 2349.1 cm^{-1} (4.3 μm) (the left hot wing of the band was used), whereas surface brightness temperature (corresponds to the emission from particles + walls) is calculated at 2600 cm^{-1} (3.8 μm) (Fig. 6). The probe was inserted into several positions inside the flame in the region near the burner. The example of the IR emission spectra at different insertion positions of the probe and the spectral ranges for the calculation of gas and particles temperatures are shown in Fig. 6. No beam stop was mounted on probe which means that the emission measured was from the gas and surfaces (particles and walls). For each position, the temperature of gases and particles was measured with the rate of 1 kHz for 10 s at each probe insertion position [10].

The temperature of CO_2 and solid surfaces was calculated according to the spectral-emission absorption method using Eqs. (5) and (2), i.e. applying Kirchhoff's and the Planck radiation laws, for every wave number point within the respective regions in the emission spectra $L_E(\nu)$ (the examples of those are shown in Fig. 6) and the value of spectral absorptance $\alpha(\nu) = 1$ for both CO_2 and solid surfaces (the grounds for the latter approximation of $\alpha(\nu) = 1$ can be found in [6]). The value of temperature at a given time point was found as a simple average of temperatures at all the wave number points within the respective region in the emission spectrum at that given time point. As mentioned previously, the emission spectra $L_E(\nu)$ were taken every 1 ms (or at the frequency of 1 kHz).

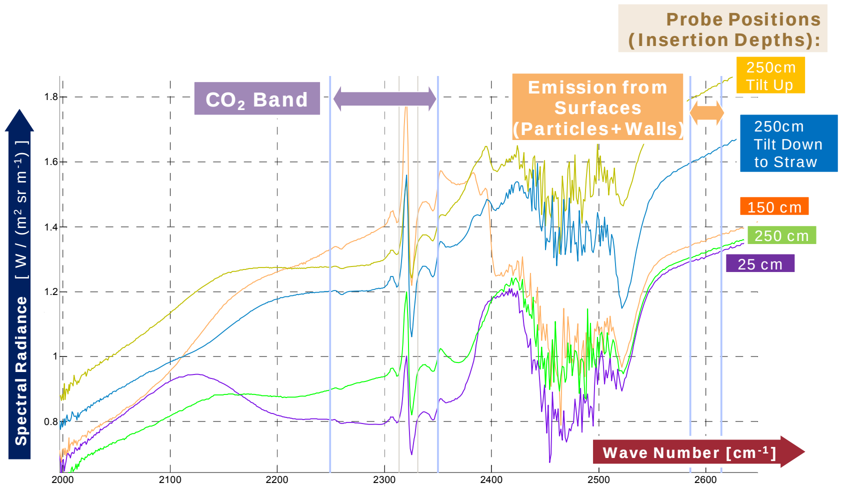


Figure 6. Emission spectra for several insertion depths of the probe: the emission was from the gas, particles and walls.

An example of measured local gas temperature and brightness temperature of surfaces (particles + walls) for probe inserted into the straw flow near the burner, i.e. inserted 250 cm from boiler wall and probe tilted downwards is shown in Fig. 7 [10].

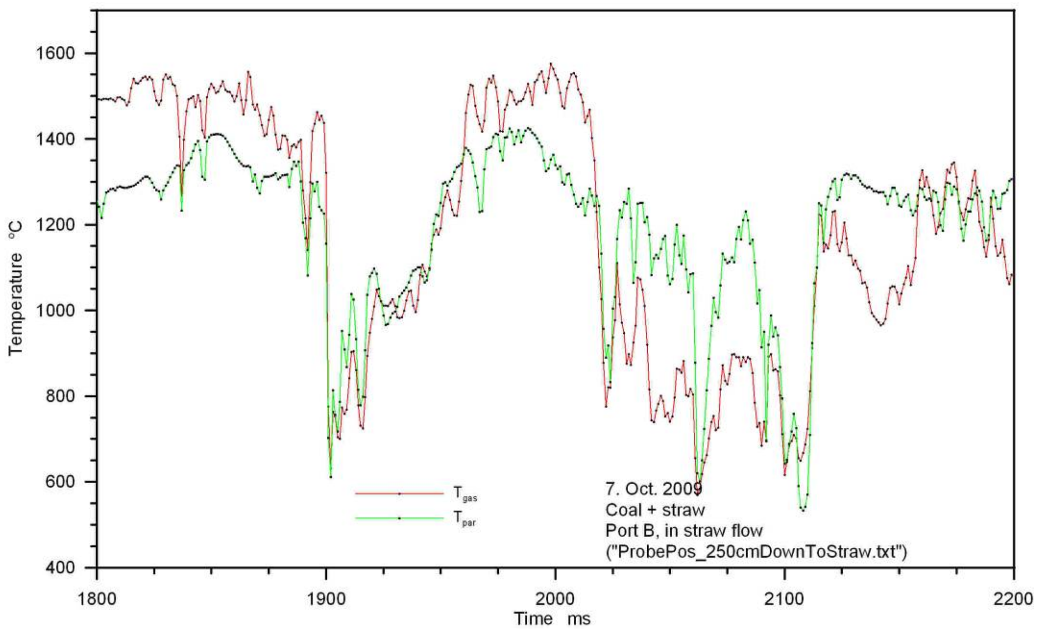


Figure 7. Example of measured local gas temperature (red curve) and brightness temperature of surfaces (particles + walls) (green) for probe inserted into straw flow near the burner, i.e. inserted 250 cm from boiler wall and probe tilted downwards. Measurement performed on 7th October 2009 at 18:00 during test programme with data rate of 1 kHz. Only 400 ms period is shown out of 10 s [10].

1 ms data rate is sufficient to resolve details in temperature fluctuations, see Figs. 7 and 8. Very large temperature fluctuations are observed for probe inserted into straw flow. Brightness surface temperatures down to 500 °C are seen when straw particles block or partial block the field

of view of probe. Gas temperature fluctuations follow to some extent particle temperature variations in zone with high density of straw. The gas temperature is sometimes less than the particles temperature, which indicates structures of the primary air are still surrounding straw particles. The fast temperature measurements show that straw feeding is jet like with very large variations in particle density at the measured position near the burner.

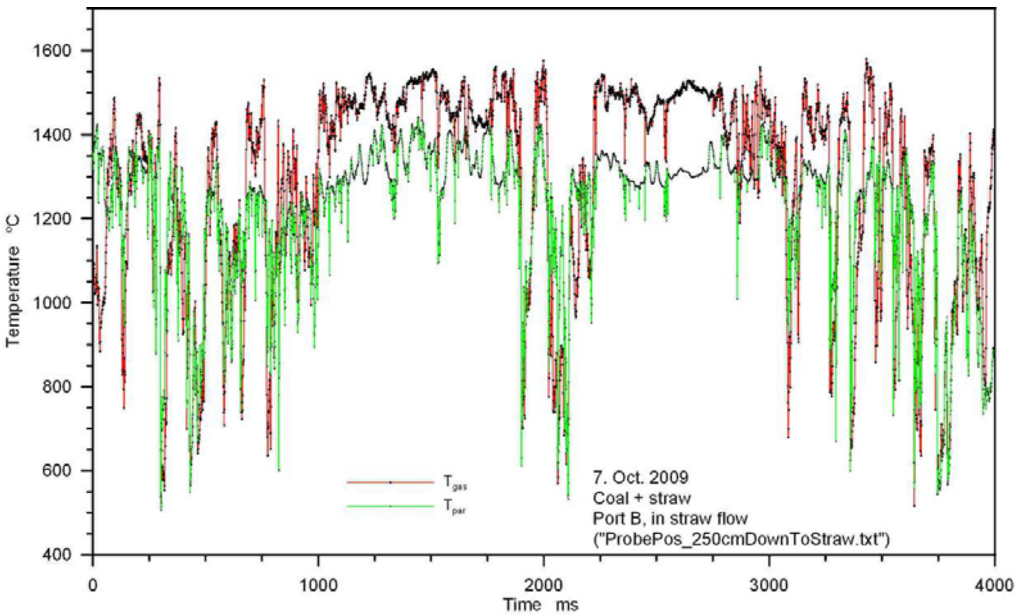


Figure 8. Measurement probe inserted over straw flow near the burner, i.e. inserted 250 cm from boiler wall and probe tilted downwards (inside straw flow) [10].

The mixing of fuel and gas in coal-straw flame could be better from a quick look at Fig. 8, i.e. periods of 0.9 s are observed with few straw particles (few spikes with low temperature). IR pictures of straw flow from burner show similar behaviour (see Section 3.1).

Measurements outside the straw flow, i.e. when the probe was inserted at 250 cm from the boiler wall and tilted upwards, are shown for comparison in Fig. 9. It can be seen that particles do not undergo as huge temperature variations as gases do. That is partially due to a higher heat capacity of particles and partially due to there is also contribution from the emission from the walls having constant temperature. Also, gas temperature is higher on average than that of the particles when compared to the case of Figs. 7 and 8. It means that the gases and the particles are not in thermal equilibrium with each other and that is the consequence of the turbulent processes in the flame.

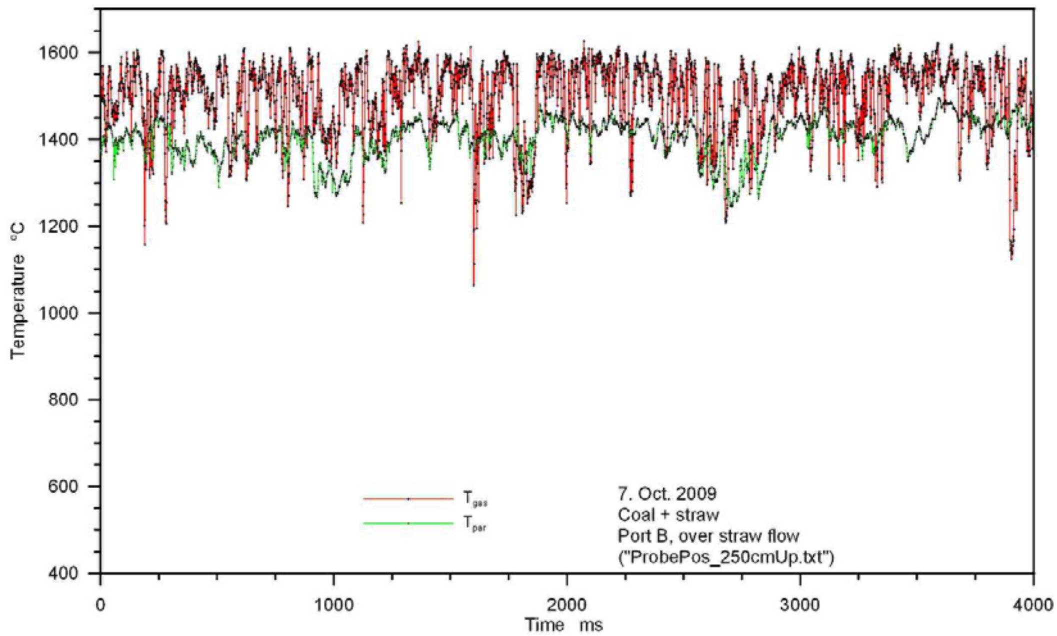


Figure 9. Measurement probe inserted over straw flow near the burner, i.e. inserted 250 cm from boiler wall and probe tilted upwards (outside straw flow) [10].

3. Other Applications of Infrared Camera

3.1. Infrared Endoscope System for Fast Thermal Imaging in Industrial Flames

The infrared camera was used together with the water-cooled endoscope optical set-up (Fig. 10) developed in project [10] for fast thermal imaging of flames in the same industrial boiler as in the case of the fast spectral measurements (Section 2.4).

The IR camera is less sensitive (by approx. a factor of 10) to thermal radiation from soot when compared to a video camera, i.e. pictures or movies of fuel particle flow in large flames can be recorded with a better quality in the middle infrared spectral region than in the visible. The thermal radiation from soot dominates in the visible region. Therefore video pictures of flames show only a “part” of a flame which has high temperature and high soot concentration (high CO and C_xH_y levels) and hence colder regions of the flame (large fuel particles) become much less distinctive on the visible region videos compared to the videos made with the IR camera sensitive at around 3.9 μm.

Figure 10. Inspection of the flame using the IR camera with a water cooled endoscope optics [10].

Brightness temperature image (emissivity was set to 1.00) of a coal-straw flame taken with a 3.9 μm optical filter is shown in Fig. 11. The temperature of the surfaces and particles of approx. 850 °C (the blue region) was observed inside the quarl region, but the surface temperatures of particles increase up to approx. 1250 °C (the green region) shortly after leaving the burner. The particle temperatures are probably significantly lower in the core of the flame which cannot be seen due to the high density of the particles [10].

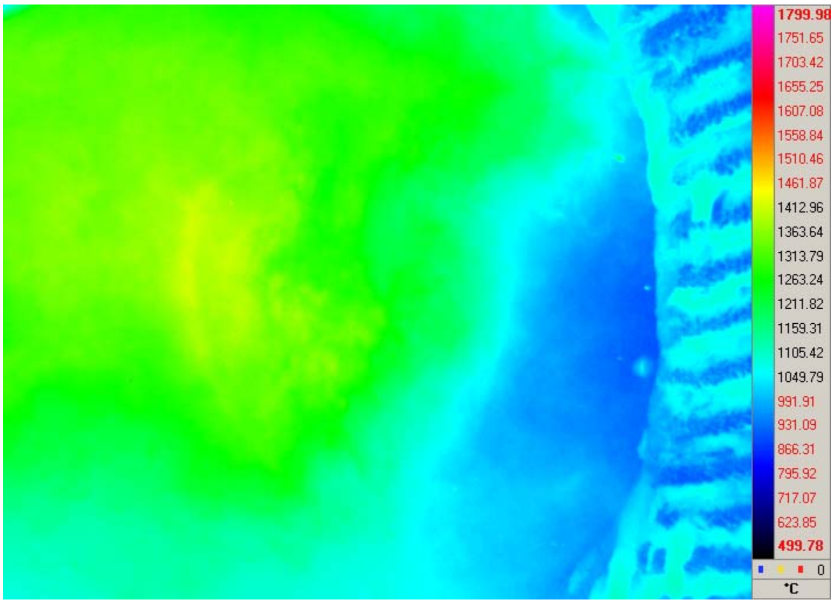


Figure 11. Thermal image of the near burner field. Fuel: coal + straw. Date: 19 Oct. 2009. The IR camera was used with the 3.9 µm optical filter. The exposure time was 24 µs. The colour scale is in °C [10].

Intensity fluctuations in the IR pictures (Fig. 12) reflect the fluctuations of the fuel-particle concentration and temperature. Fluctuations have approximately a 1/f noise power spectrum, i.e. frequency spectrum is inversely proportional to the frequency. The "1/*ƒ*-like" noises occur widely in nature. In this system, it can be seen as a long-term effect where something suddenly happens like straw moves from one side of burner to another, or suddenly there is no straw flow, etc. [10].

The surface temperature of the coal-straw flame (fuel particles) in the burner region is lower than that of the pure coal flame. Similarly, the upper part of coal-straw flame is hotter than the lower part. The temperature field of the coal-straw flame is less stable and has large structures in the temperature field which is the indication of the fact that the ignition sometimes happens outside the burner [10].

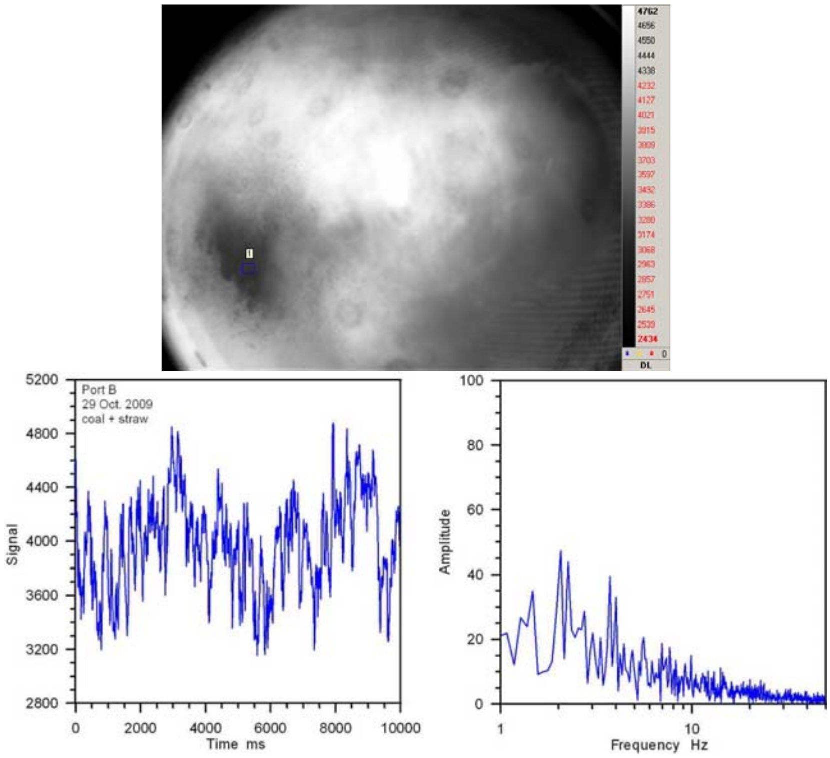


Figure 12. Example of intensity fluctuations taken from the thermal images (1000 frames) of the flame. The area of interest is shown with the blue rectangle on the thermal image. The fluctuations have approximately a 1/f noise power spectrum (f is the frequency [Hz]) (the plot on the right-hand side) [10].

The distribution of the straw particles is still not uniform in the tale of the flame as seen from the images recorded at port D (6.72 m from the burner wall) (Fig. 13). Large moving structures with high concentration of straw particles are still seen. This behaviour can cause problems with poor conversion of straw particles as particles transported in structures with low temperature and thermal heat transfer by radiation to particles is strongly reduced [10].

The velocities of the moving structures can be found if the distance to the structures is known, e.g. a lump of straw particles close to particle sampling probe tip is seen in first 2 images shown in Fig. 13. Δx = 0.18 m (structure close to 18 cm wide tip of probe and moves horizontal) and Δ= 20 ms (two frames between images) giving a velocity of 9 m/s [10].

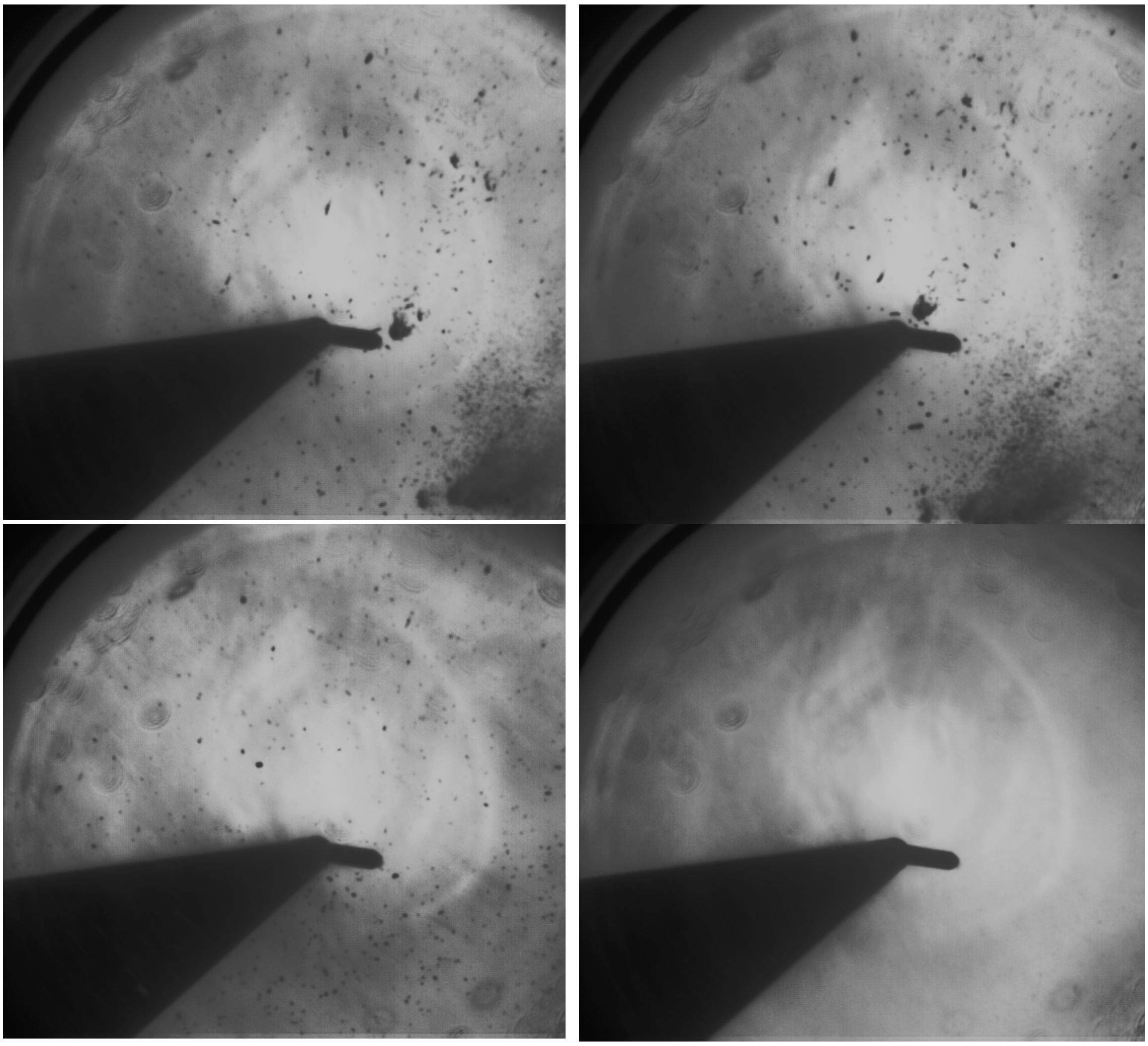
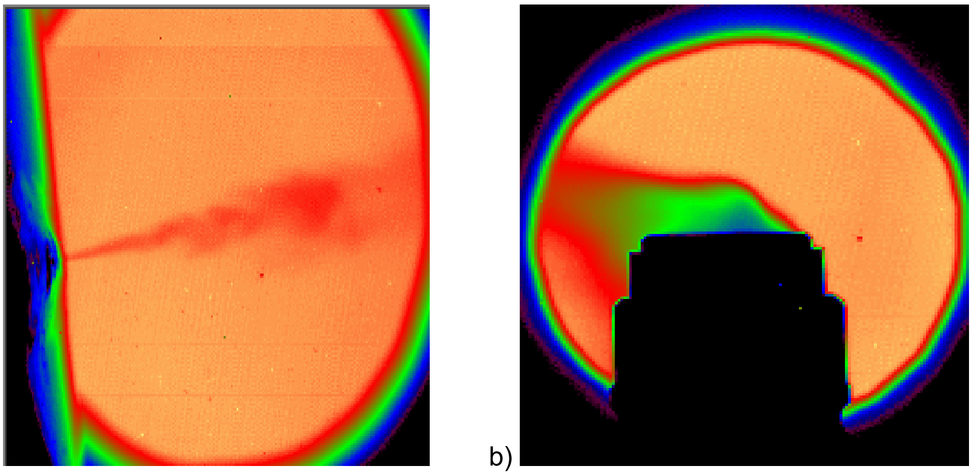


Figure 13. Straw particles seen from port D: frames 944, 946, 986 and 786 (no straw particles seen). Probe for sampling of particles, seen in pictures, was inserted 1.5 m. Endoscope optics mounted on the IR camera, the 3.9 µm optical filter, 100 Hz recording rate of pictures and 333 µs exposure time [10].

3.2. Gas Leak Imaging and flow visualisation

The infrared camera can also be used for the imaging and detection of the gas leak or visualisation of hot/cold gas flows. Fig. 14 shows an example of gas leakage detected with the IR camera from a hole in a ga bottle (a) and from a seal which is not sufficiently tight (b). The cold gas can be seen against hot background. Special filters must to be used in order to be able to detect various gases. For example, the 3.4 µm filter can be used to detect hydrocarbons, and a 4.35 µm filter for CO_2 (figure 15).



a) b)

Figure 14. Gas leak from gas bottles can be imaged with the IR camera. The cold gas is seen against hot background. a) The small hole in the gas bottle is detected (red jet seen); b) the seal of gas bottle is not tight (blue-green-red area).

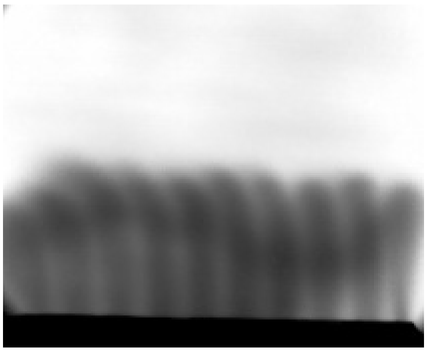


Figure 15. Visualisation of gas flow distribution to a test fuel cell (black area below) with CO_2. 10 single jets are seen. Same jet heights mean uniform gas flow into the fuel cell. Live movie of jets can be studied.

3.3. Simultaneous Fast Infrared Spectral Measurements at the Three Optical Ports of the Exhaust Duct of a Marine Diesel Engine

A multichannel infrared spectroscopy system was developed at DTU Chemical Engineering for simultaneous fast IR measurements on several lines of sight. The system was applied for fast simultaneous infrared spectral measurements at the three optical ports of the exhaust duct of a cylinder on a test marine Diesel engine at MAN Diesel & Turbo, Copenhagen [12]. Simultaneous exhaust gas temperature for every port as a function of time (the same time points for all three ports) was calculated from the simultaneous emission spectra using the spectral emission-absorption method (Section 2.3) which provided useful information for further analysis of combustion in the engine.

The system is the same as described in Section 2.1 and optimized to work in the same spectral region except that three optical fibres are coupled to the entrance slit of the grating spectrometer (Fig. 16) with the aid of a dedicated mechanical adaptor. The adaptor is optimized for three fibres which was the requirement of the application on the engine as mentioned above (three optical ports) but it is possible to couple more fibres. Thus, the system is capable to carry out the IR measurements simultaneously on the three lines of sight.

The temporal resolution of the IR measurements, as mentioned in Section 2.1, is determined by the exposure time (frame rate) of the camera which is generally dependent on frame size. The frame size must be sufficient to cover the infrared image obtained from the three optical fibres. Taking account of the distance between the fibres at the slit, the camera's frame rate can be up to 500 frames per second which is 2 ms of temporal resolution.

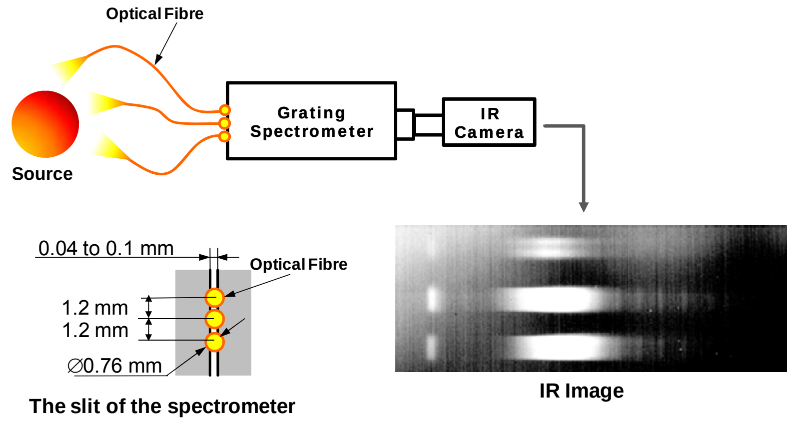


Figure 16. Multichannel Infrared Spectroscopy System.

The work on Diesel engine, based on a modified version of the developed system in this project, will be published in 2012 in two separate publications, i.e. fast gas measurements and visualisation of hot gas flow in cylinder of MAN Diesels large test engine during operation under extreme conditions (2200°C, 160-180 bars).

4. Conclusions

An infrared spectrometer system has been developed for fast spectral measurements and imaging.The system was successfully tested on a flame in the laboratory, and applied on industrial scale, in industrial boilers, large diesel engine, etc. The system was applied for fast spectral measurements in a full-scale coal-straw flame. The gas and fuel temperatures were obtained at high temporal resolution. The measurements provided essential data for further diagnostics and optimization of the combustion process, e.g. very large gas temperature fluctuations from 500-1600°C in a flame over one second indicate poor mixing or instable flame. Poor mixing of gas and fuel and temperature fluctuations in flame affect formation of thermal NO and can cause problems with CO emissions and poor burn-out.

The infrared camera used in the project was also applied for fast thermal imaging in the industrial boiler using special endoscope optics. Special adaptor optics was designed to couple the IR-camera with custom optics. The infrared images of the flame in the boiler provided useful data for the diagnostics in the near-burner zone, i.e. good quality pictures of fuel distribution from the IR-camera can be overlaid with visual pictures (video) of ignition of flame. The developed system is a power-full tool for optimising pulverised bio-dust flames, and will be used in on-going research projects at DTU KT. The system has so far been used on full-scale pure coal (air and oxy-fuel), coal-straw, wood-coal and pure wood pulverised flames. Large scale fuel structures with poor mixing of gas and fuel is observed for most flames. Another observation is that most flames are not symmetric. Flame symmetry can affect formation of pollutants (thermal NO).
The system is planed to be used in DSF-project “GREEN” for fast thermal imaging of wood dust flames started up in 2011. The system can be used to study effects of burner settings and burner designs (activity in 2012).

The infrared camera system has many other useful applications. For example, it can be used for gas flow visualisation and gas leak detection.

The infrared spectrometer system developed in the project was further developed in EU-project “Hercules Beta” by coupling three optical fibres on the entrance slit of the spectrometer allowing fast simultaneous infrared spectral measurements from three lines of sight. The new multichannel infrared spectroscopy system was successfully applied for fast simultaneous infrared spectral measurements at the three optical ports of the exhaust duct of a test marine Diesel engine. The exhaust gas temperatures as functions of time were obtained at high temporal resolution simultaneously at the three ports. Good agreement of dynamic gas temperatures measurements with a UV-spectrometer was observed. The system can be extended from 1-3 channels up to approx. 8 channels, i.e. temperature or gas concentration can in principle be measured simultaneously with a exposure time of 7 – 1200 μs with the system developed. The infrared system has also applied for fast thermal imaging

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